Reference Path Description for an Autonomous Powered Wheelchair

J. D. Yoder
Graduate Assistant
U. of Notre Dame

E. Baumgartner
Assistant Professor
Michigan Technological U.

S. B. Skaar
Associate Professor
U. of Notre Dame

Abstract

This paper presents an overview of the methods used with an experimental prototype of an autonomous powered wheelchair. The paper focuses on the importance of describing reference paths as continuous (or piecewise-continuous) geometric entities, rather than as a function of time or a series of discrete points. Furthermore, the importance of using the current estimated position and orientation of the wheelchair in order to select the reference point on the path is examined.

1 INTRODUCTION

The rehabilitation field is one in which there exists significant opportunity for robotics to serve humankind. For instance, due to certain combinations of disabilities, some individuals find it difficult, tedious, or impossible to use a joystick (or other standard user-input device) to guide a powered wheelchair through the precise trajectories which are typically required for navigation within a home or office environment. These same individuals may, however, have the ability to complete the less stringent task of selecting a desired destination from a menu. If an automatically-guided vehicle (AGV), specifically a wheelchair, were able to track a path to that desired destination, the individual would clearly be given an increased degree of independence.

A prototype of such a system has been developed at the University of Notre Dame [1][2]. The system employs an extended Kalman filter to produce ongoing estimates of the vehicle's pose (its position (X,Y) and orientation (ϕ), also referred to as posture). The system then uses these estimates along with a simple model of the powered wheelchair's controller to accurately follow a trajectory. Although this paper presents an overview of the system, it will concentrate on the method used to describe and track paths. This system's success depends on the fact that it represents the wheelchair's nominal (or reference) path as a piecewise-continuous geometric entity, rather than as a function of time or a series of poses. This representation allows the system to select the current reference point (the reference point is the point on the reference path which represents the desired position and heading of the vehicle) based on estimates of the wheelchair's pose, and allows the velocity of the wheelchair to be adjusted without affecting the system's ability to track a path.

2 BACKGROUND

The general navigation problem can be summarized by three questions: 1) Where am I?, 2) Where am I going?, and 3) How should I get there? [3]. Many navigation methods have been developed in the general research area of mobile robotics. Most AGVs currently in use in industry[4], as well as a wheelchair system[5], solve the navigation problem by following guide tracks painted on or embedded within the floor of the robot's environment. Due to their inflexibility to changes in the environment, the limited variety and complexity paths which they can follow, and their inability to account for tracking errors, these systems are impractical for a home or office environment. Other mobile robots have been developed for use in an unstructured environment using proximity-type sensors such as sonar or infrared sensors and/or vision. These systems are typically developed for either outdoor use (road following) [6] or indoor use [3][7][8]. The mobile robots developed for use within indoor environments typically suffer due to the need to build up accurate maps of the environment. Any inaccuracy or imperfection in these maps will degrade the performance of the mobile robot.

Another group of research tries to answer the question "Where am I ?" by employing a set of "beacons" at known locations within the environment. These systems typically use infrared emitters [9] or laser scanners to read bar codes around the environment[10]. These two systems use a triangulation of the measurements to provide pose estimates, which makes these systems very sensitive to measurement errors. Another system, which uses geometric landmarks as beacons, attempts to solve this problem through the use of an extended Kalman filter to combine knowledge from the beacons with odometry information [3]. However, sonar is used as the primary sensor in this system. To provide accurate estimates, great care must be taken not to misidentify a beacon, and most of the sonar readings must be discarded. Furthermore, sonar sensors have been found to produce spurious distance measurements, especially in cluttered environments, due to a phenomenon known as specular reflections [11].

3 APPROACH

A method of addressing the navigation problem has been developed for an autonomous wheelchair system [1][2]. In addition to the difficulties present in the general navigation problem, an autonomous wheelchair has special requirements. For example, the system cannot simply avoid all objects in the environment and try to follow a clear path, since the system must be able to approach certain objects, such as a desk, table, or refrigerator. This application also requires that the system be highly accurate and repeatable. For example, being a few inches off of the reference path in a factory corridor may be acceptable for many AGVs, but straying a few inches as a wheelchair passes through a doorway could be damaging or disastrous. Furthermore, the system must provide a smooth ride, with small accelerations, since it carries a human passenger.

The accuracy required for the wheelchair application demands very precise estimates of pose (i.e., a very good answer to the question "Where am I?"). The experimental wheelchair system is pictured in Figure 1. This wheelchair is driven by two rear wheels which are actuated independently for steering control. For this drive configuration, shown schematically in Figure 2, a set of differential equations which relate the differential wheel movement of the two drive wheels to the differential position and orientation of the wheelchair have been derived [1][2]. These differential equations can be integrated numerically by measuring the wheel motion of the two drive wheels using optical shaft encoders. In Figure 2, the position of a point on the wheelchair is denoted by X and Y, while the orientation of the wheelchair is denoted by ϕ. Estimates of the wheelchair's pose produced by this numerical integration have been referred to in the literature as "dead-reckoning." However, if there are any initial estimation errors, modelling errors, or disturbances (such as wheel slippage), then errors in the wheelchair's pose estimates produced by dead-reckoning will grow as the wheelchair travels throughout its environment. Therefore, some type of observation or measurement of the surrounding environment must be made to correct any errors in the dead-reckoned estimates of the wheelchair.

Two video cameras are placed below the seat of the wheelchair to observe visual cues which are located at discrete positions within the environment. Using a pin-hole camera model, the horizontal position of a cue in the image plane of each camera is related algebraically to the pose of the wheelchair within its environment. Small ring-shaped, elliptical patterns are used as the visual cues (passive "beacons") for the wheelchair system. These cues are typically affixed to walls, approximately one foot above the ground. The locations of these cues are the only *a priori* information about the environment that the system requires in order to obtain accurate pose estimates. These patterns are chosen because they are rapidly and robustly detectable from a digitized image. Through an algorithm known as the extended Kalman filter [12], the observations of the visual cues are used to update and correct the estimates of the wheelchair's pose based on dead-reckoning alone. For the wheelchair system, the extended Kalman filter typically produces position estimates which are accurate to within an inch and orientation estimates which are accurate to within one degree [1][2].

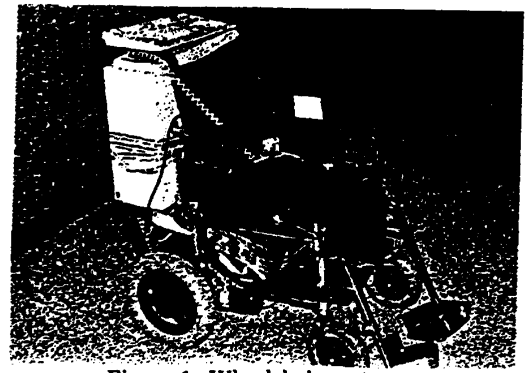
Figure 1: Wheelchair system

Based on the accurate pose estimates produced by the extended Kalman filter, desired reference paths are "taught" to the vehicle. The wheelchair system is taught by manually guiding the wheelchair through the desired path. During the teaching procedure, estimates of the wheelchair's pose are generated. The taught path is then saved in a manner which is compatible with a tracking procedure which in turn is used to repeat the taught path. Many paths which would take the user from one station to another in the home or office would be taught and recorded during a one-time teaching session. The use of a teacher by the wheelchair system allows the judgement of the teacher to be invoked. Humans are very adept at controlling nonholonomic or mobile systems, especially for tight-tolerance maneuvers (e.g., maneuvering to approach a desk or pass through a door). Therefore, the use of a human to teach paths which take the wheelchair from station to station provides a high level of path planning capability which is otherwise difficult to achieve. The system has been successfully taught complex maneuvers in a tight office setting and, using the path

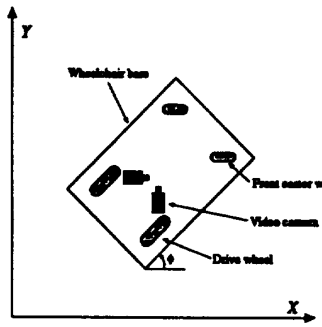

Figure 2: Wheelchair schematic.

tracking algorithm described below, the system has successfully followed taught paths in a precise and reliable manner. Another strength of this method of defining paths is that the same estimation algorithm is used both to generate a description of a path, and then to track the same path. This decreases the effects of any error in the measurement of the absolute position of the visual cues.

The wheelchair system described above has been successfully developed and tested both in a laboratory and an office setting. Video documentation of the wheelchair system while navigating throughout an office setting is available from the authors. Everest & Jenning's Tempest model powered wheelchair is used as the experimental wheelchair platform. An 80386-based personal computer placed on-board the wheelchair carries out the image processing, wheel-rotation sensing, pose estimation, teaching of reference paths, and tracking of taught reference paths, all in real-time. Two CCD video cameras placed below the seat of the wheelchair view the ring-shaped cues which are placed at discrete locations within the wheelchair's environment. Also, optical shaft encoders roll on the two drive wheels to measure the drive wheel rotations. Control of the drive wheel motors is accomplished by interfacing the personal computer directly with the wheelchair's joystick control box.

4 PATH DESCRIPTION

Once accurate estimates of vehicle pose become available, the questions of "Where am I going?" and "How do I get there?" must still be addressed. Typically this is accomplished by specifying a path for the vehicle to follow. The way in which this path is described is critical to the success of the system. It should be noted that the path description involves the representation of the path itself as well as the method used for selecting a reference point on that path.

4.1 TIME-BASED DESCRIPTION

Many systems choose to describe the reference path as a function of time [13]. At a given time, then, the vehicle compares its current pose ($X(t)$,$Y(t)$,and $\phi(t)$) to the desired pose ($X_{ref}(t)$,$Y_{ref}(t)$,and $\phi_{ref}(t)$) and attempts, through a control algorithm, to eliminate the difference. Although this method may work well when only small disturbances are present, it seems to suffer from several problems as tracking errors become large. The first, and likely most serious, flaw of this method is that there may develop a lag (or lead) between the reference point on the path and the actual location of the vehicle. On a straight path, this would not be a problem. However, on a path with significant curvature, this would result in the vehicle "cutting corners" of the path. Clearly, for tight tolerance paths, this behavior would be unacceptable. Another, similar, problem can be seen in that, generally, when a path is planned, inertial considerations and the comfort of the user dictate that the reference velocity be reduced for sections of the path with high curvature. If this reference velocity is also a function of time ($v_{ref}(t)$), then a lag (or lead) of the vehicle compared to the reference could lead to high velocities in areas of high curvature and low velocities in areas of low curvature, precisely the opposite of what is desired.

One possible response to these problems would be to suggest that by servoing the velocity of the system, any lag (or lead) could be avoided. However, this approach also encounters several problems. First, since infinite accelerations are not possible, there clearly will be some response time during which a lag (or lead) will persist. Second, the frequent acceleration and deceleration required by this approach would result in a very jerky, uncomfortable ride. Comfort could be improved by setting an upper bound on the system's accelerations, but this would again require that a considerable lag (or lead) be allowed. It is also worth noting that the Kalman filter instantaneously changes the estimates of the pose when a new observation is made. If a time-based path description is used, this change could "create" a lag (or lead) even if none were present due to tracking errors alone.

The last problem raised by specifying the reference path as a function of time is that this precludes the possibility of changing the velocity during path-tracking for other reasons. Doing so would clearly generate the type of lag (or lead) described above. Yet the ability to change velocity is very important in order to maintain accurate estimates. As the vehicle progresses, its ability to maintain accurate estimates depends in part on the number of observations which can be made. If the covariance matrix (and hence the uncertainty of the estimates) becomes exceedingly large, the system should try to improve its estimates without travelling an excessive distance. For a given measurement system, the number of observations which can be made per unit time is fixed. Therefore, the only way to acquire more observations while travelling a given distance is to slow down. This will allow denser observations to be made, improving estimate accuracy, and eventually allowing the system to return to full speed [14].

4.2 POINT-BASED DESCRIPTION

Another possible method of describing the reference path would be to simply describe the path as a series of discrete poses [15]. This method is similar to the one most often employed by holonomic robots to follow a trajectory. The method waits for the vehicle to get sufficiently close to a point (say, to within ϵ), and then commands the vehicle to move toward the next point of the reference path. This method would not suffer from the possibility of the vehicle lagging (or leading) the reference point, since the reference point would only advance once the vehicle was sufficiently close to the current reference point. Furthermore, this method would allow for independent specification of the nominal velocity, allowing the vehicle to slow down in order to improve the accuracy of its estimates.

This method does suffer from several other shortcomings, however. Unlike holonomic robots, inverse kinematics are not available to uniquely determine the drive wheel rotations required to move from the current estimated position to the next reference point. A planning routine would have to be incorporated to select a possible path for the vehicle to travel in order to get to the next reference point. Note that to ensure continuity when the next point would be reached, such a path-planning algorithm would also need to consider the next reference point. This planned path would somehow have to be represented, possibly by a time-based description, in which case nothing has been gained by using a point-based description. Alternatively, the vehicle could pivot at the current point until its heading is toward the next point, and then proceed towards that point. Due to tracking errors, a series of pivots and moves would most likely be required. Clearly, this sort of path-tracking would not yield a smooth or enjoyable ride. A third possibility would be to select a desired heading (ϕ_{ref}) toward which the vehicle would steer while maintaining some forward velocity. This would allow for a somewhat smoother ride, but would lead to jerks in the ride at each reference point when (ϕ_{ref}) changes instantaneously. If this change were large enough, it could also lead to large tracking errors.

Another problem encountered by any method which uses a series of points to represent the path is due to the previously described problem of instantaneous changes in the estimates. Such a change could produce the situation in which the vehicle estimates its position as being beyond the point toward which it was moving (the estimated position "jumped" forward along the path). Clearly, the vehicle should not back up, but the criterion that it be within ϵ of a reference point to move on has not been satisfied. Some means

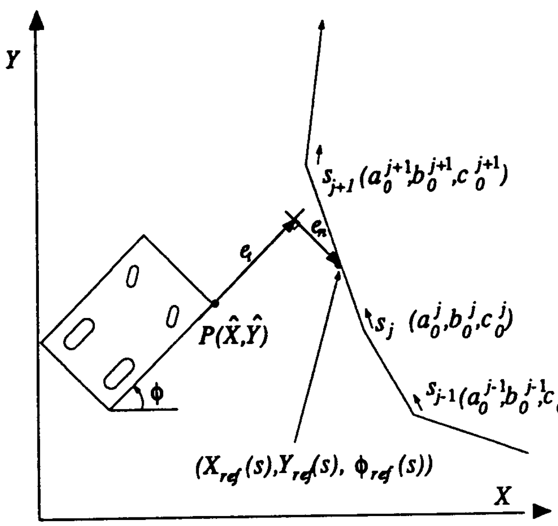

Figure 3: Reference path description.

of picking which reference point to use would have to be implemented. At the other extreme ("jumping" backward), the change in the estimates could result in moving towards a point which is not the nearest point to the estimated pose of the vehicle. This would clearly lead to "cutting corners" as described above.

4.3 GEOMETRY-BASED DESCRIPTION

The autonomous wheelchair system uses a different way of representing the reference path which addresses the above problems. Linear functions of the arc length of the path are used to represent segments of the desired reference path as shown in Figure 3. Thus, for the j^{th} path segment,

$$X_{ref}(s_j) = a_0^j + a_1^j s_j \tag{1}$$

$$Y_{ref}(s_j) = b_0^j + b_1^j s_j \tag{2}$$

$$\phi_{ref}(s_j) = c_0^j + c_1^j s_j \tag{3}$$

where $0 \leq s_j < 1$ for $j = 1, ..., J$, where J represents the number of segments in the reference path and the parameters a_0, a_1, b_0, b_1, c_0, c_1 are produced during the teaching procedure. Thus, the entire sequence of pose estimates which are generated during the teaching of the desired reference paths is compressed into J first-order (i.e. straight-line) segments (Note that because position and orientation are not independent over the course of any given segment, small incompatibilities may be present). Having represented the path in this way, a reference point on the path must be selected, and a way of steering towards it must be provided. For this system, the above task is accomplished purely geometrically, based on the estimated pose of the wheelchair and the stored representation of the reference path.

As shown in Figure 3, navigation of the vehicle can be based upon tangential, normal, and angular errors between the vehicle and the desired reference path. For a given path segment, the tangential, normal, and angular errors between an arbitrary point, P, on the vehicle and a point on the reference path are given by

$$e_t = (X_{ref}(s) - \hat{X})\ \cos\hat{\phi} + (Y_{ref}(s) - \hat{Y})\ \sin\hat{\phi} \quad (4)$$

$$e_n = (X_{ref}(s) - \hat{X})\ \sin\hat{\phi} - (Y_{ref}(s) - \hat{Y})\ \cos\hat{\phi} \quad (5)$$

$$e_\phi = \phi_{ref}(s) - \hat{\phi} \quad (6)$$

where $\hat{X}$, $\hat{Y}$, and $\hat{\phi}$ represent estimates of the position of a point P on the vehicle and orientation of the vehicle as determined by the extended Kalman filter. For some time-based controllers, the tangential error is used to control the speed that the vehicle travels along the reference path. For this algorithm, however, e_t is specified in order to determine the reference point on the path. At any instant, the estimates of position and orientation are known. Therefore, the only unknowns in equation (4) are e_t and s. For example, choosing $e_t = 0$ in equation (4) and using equations (1) and (2), equation (4) yields

$$e_t = 0 = (a_0 + a_1 s - \hat{X})\ \cos\hat{\phi} + (b_0 + b_1 s - \hat{Y})\ \sin\hat{\phi} \quad (7)$$

where a_0, a_1, b_0, and b_1 are known from the reference path teaching procedure. Expressing (7) in terms of s yields

$$s = \frac{-[(a_0 - \hat{X})\ \cos\hat{\phi} + (b_0 - \hat{Y})\ \sin\hat{\phi}]}{[a_1\ \cos\hat{\phi} + b_1\ \sin\hat{\phi}]} \quad (8)$$

where s is the value of the arc length along the reference path of the point to be used as the current reference. Once the value of s is known, the normal error, e_n, and the orientation error, e_ϕ, can be determined via equations (5) and (6), respectively. By choosing $e_t = 0$, the value of s given by equation (8) yields the position along the path which is intersected by a line normal to the vehicle passing through point P. If $e_t > 0$, then the vehicle, in a sense, looks ahead along the path to determine which position on the path to control towards. The commanded control variable, u, is then determined by passing the normal and angular errors through a standard PID controller. The desired drive wheel velocities, $\dot{\theta}_{nom_r}$ and $\dot{\theta}_{nom_l}$, to be commanded to the motor controller are then found by the following relationships:

$$\dot{\theta}_{nom_{r,l}} = \frac{d\theta_{nom_{r,l}}}{dt} = \frac{v_{nom}}{R}\ (1 \pm u) \quad (9)$$

where v_{nom} represents the separately-determined commanded speed of the midpoint (along the axle) of the two drive wheels, and R is the drive wheel radius (assuming identical wheels). The nominal drive wheel velocities, $\dot{\theta}_{nom_r}$ and $\dot{\theta}_{nom_l}$, are then fed to the vehicle's motor controller. Here it is clear that the nominal velocity can be adjusted without affecting the path-tracking ability of the system. While the path is being tracked, this velocity can be adjusted based on the curvature of the path,the current confidence in the estimates (as determined by the covariance matrix), or other considerations.

The above formulation assumes the system has a method of determining which path segment to use in order to find the reference point. The simplest way to do this would be to start at the first path segment, and increment the reference path segment each time $s > 1$. In practice, two problem arise when using this algorithm. First, when e_n (normal error) becomes sufficiently large, s would decrease as the vehicle turns to return to the path. In practice and in simulations, it was found that such behavior could lead to instability. The simple restriction that s can never decrease was added to the algorithm to preclude this possibility. Secondly, incrementing the path segment whenever $s > 1$ allows the vehicle to skip portions of the path in sections of high reference path curvature. In order to avoid this, the vehicle estimates its distance from the line which is perpendicular to the current segment and which crosses through the end of the segment. When this distance is less than or equal to 0, the next reference segment is used. This strategy ensures that each segment will be tracked until the vehicle is, in some sense, at the end of that segment. The routine is used recursively to ensure success even if the estimates change suddenly.

The above geometric method of describing and tracking the path has allowed the system to accurately track a variety of tight-tolerance paths in a laboratory, an office, and an apartment. Typically, these trajectories require the system to pass through doors and approach to within inches of desks and tables. The system has succeeded in tracking paths despite external disturbances (running over electrical cords or small boards) and widely varying loads (from no rider up to a 190 lb rider). Although the prototype needs further development, its present success is largely due to the way in which it describes the reference path.

It should be noted that space limitations prohibit full description of alternative path-description methods in this paper. Others have tried to represent the path geometrically, but without careful selection of the reference point, problems similar to those described in sections 4.1 and 4.2 would be encountered. Furthermore, by "slowing" or "speeding" time, time-based descriptions could produce good results, but these adjustments would have to be made via geometric considerations such as those described in this paper. Similarly, point-based representations could be used if geometric considerations were used to interpolate between the points (eliminating discontinuities) and to select the current reference point.

5 SUMMARY

A brief overview of the methods used by a working prototype of an autonomous powered wheelchair system has been presented. The system uses a time-independent extended Kalman filter based on odometry and visual observations of cues to provide precise pose estimates in a structured environment. Using these estimates during a "teaching" mode, a geometric representation of a reference path is created and stored. Using this representation, along with accurate estimates, the system is able to track reference paths accurately and smoothly despite large disturbances or sudden changes in the estimated position and/or orientation. Furthermore, this method allows the velocity to be adjusted while the path is being tracked if more accurate estimates are required.

Further work is needed to bring this system to the point where it can be used practically. Proximity-type sensors must be incorporated to sense obstacles and avoid collisions. The computer must be downsized, and an interface must be implemented which allows a large range of user-input devices to be used. However, these problems can be solved, and doing so may bring the system to the point where disabled individuals can take advantage of such a device. In much the same way that powered wheelchairs allowed individuals, who could not navigate using standard wheelchairs, to become independent, it is hoped that the methods and device described in this paper would give those who cannot steer a powered wheelchair the ability to navigate throughout a structured environment.

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